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14. ABSTRACT

An international conference on "Thermal and Environmental Barrier Coatings" was held at the Swabian Conference Center, Irsee, Germany under the auspices of Engineering Conferences International and with partial financial suport from both the Air Force Office of Scientific Research and the Office of Naval Research.
The conference was the first international conference on the subject open to the materials community at large. Previous workshops had been held on specific research initiatives and, particularly in Europe, were related to National programs.
The conference attracted scientists and engineers from twelve countries, as well as fourteen graduate students from the US and Europe, carrying out research on a variety of topics related to the performance of current thermal barrier systems and the development of new materials and techniques for future thermal barrier systems. The active participation of engineers from the major gas turbine companies (Rolls Royce, Ge, Pratt and Whitney, Siemens, Alstrom) as well as researchers in Government laboratories and academics in fundamental areas of science underpinning the application and development of thermal barrier coatings ensured a lively exchange of ideas and experience, as well as the identification of major areas of emphasis for future

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Report to

Air Force Office of Scientific Research

On

Conference

Thermal and Environmental Barrier Coatings

held

August 17-22nd, 2003

At

Kloster Irsee,
Swabian Conference Center,
Germany

David R. Clarke
Materials Department, College of Engineering
University of California, Santa Barbara

EXECUTIVE SUMMARY

An international conference on "*Thermal and Environmental Barrier Coatings*" was held at the Swabian Conference Center, Irsee, Germany under the auspices of *Engineering Conferences International* and with partial financial support from both the Air Force Office of Scientific Research and the Office of Naval Research.

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The conference attracted scientists and engineers from twelve countries, as well as fourteen graduate students from the US and Europe, carrying out research on a variety of topics related to the performance of current thermal barrier systems and the development of new materials and techniques for future thermal barrier systems. The active participation of engineers from the major gas turbine companies (Rolls Royce, GE, Pratt and Whitney, Siemens, Alstrom) as well as researchers in Government laboratories and academics in fundamental areas of science underpinning the application and development of thermal barrier coatings ensured a lively exchange of ideas and experience, as well as the identification of major areas of emphasis for future material systems. (These are listed in the section on recommendations that follows).

One of the major conclusions of the conference was the realization amongst many of the participants that an integrated materials systems approach will be essential in the development of more reliable, higher temperature capability thermal barrier systems for future applications. The high temperatures, the consequential inter-diffusion dynamics, and the severe temperature gradients result in strong coupling between the mechanical, thermal, chemical and optical properties of the materials over the life of coating and so are making the design of future coatings for both metallic and ceramic components one of the major challenges in aerospace materials.

No conference proceedings were issued but each participant received a copy of the abstracts.

Conference Objectives

An important juncture has been reached in the development of thermal barrier coatings. "First generation" thermal barrier coatings, based on yttria-stabilized zirconia (YSZ), are already in widespread use both in propulsion turbine engines (marine and aerospace) and power generation gas turbines. Up to now, their functionality has largely been to extend the life of turbine components, such as blades, vanes and combustors, by reducing the metal surface temperatures by insulating their surfaces thermally. However, there is a growing recognition that to increase engine performance further, coatings capable of operating at considerably higher gas temperatures are required. This requires new coating materials with superior high-temperature capabilities. One of the objectives of the conference was to address the scientific challenges to the materials community required to identify such materials.

The challenges in identifying potential materials are numerous and range from the identification of oxide materials with unprecedented lower thermal conductivity at high temperatures, understanding the lateral strains associated with oxidation of multi-component alloys, understanding the driving forces for the observed morphological instability of systems consisting of multi-layer coatings, designing diffusion barriers and incorporating them during the manufacture of the coatings, and designing coatings that can resist both oxidation and corrosion. In addition, there is the challenge of developing mechanism-based fracture mechanics models and associated non-destructive testing methodologies for applying the scientific understanding in creating reliable models that can be used in industry. Progress has been made in some of these areas but in others the challenges are just being recognized and formulated. The interdisciplinary nature of these questions, their broad scope, ranging from ceramics to metals and interfaces, as well as the challenges involved in the developing a systems understanding to their inter-related behavior in a coating system makes this the most exciting scientific area in structural materials today. In addition to capturing the excitement in this vigorous new field of high-temperature materials, one of the Conference objectives was to clarify the specific materials challenges and the progress being made in addressing them.

It is now recognized that in addition to identifying potential new coating materials, there are formidable scientific challenges to the development of coating systems with superior high temperature capabilities. These challenges stem from the changes that can occur in response to the high temperatures and large temperature

gradients to which future coatings will be subject. One of the objectives of the conference was to bring together scientists and engineers actively participating in these challenges with experts from related scientific fields needed to advance the field of coatings.

A fourth objective of the Conference was to consider the prospects for non-contact sensing of coatings, for instance to assess damage, local temperatures and aging of the coating microstructure.

Principal Findings and Recommendations

1. The cyclic oxidation life of current YSZ coatings is rarely limited by the degradation of the YSZ coating itself.
2. Current coatings either fail by morphological instabilities, such as "rumpling", of the underlying bond-coat alloys or as a result of the thermally grown oxide (TGO), formed by oxidation of the bond-coat, attaining a "critical thickness" of about 6-8 microns.
3. These findings suggest that enhanced cyclic oxidation life with present YSZ coatings can be substantially increased by improving the oxidation resistance of the bond-coat alloys and by limiting the processes that drive "rumpling" instabilities.
4. Thus, one major recommendation is that greater effort be expended on understanding the basis of "rumpling" and the development of more oxidation-resistant bond-coat alloys.
5. Phase compatibility with the oxidation product formed on the boat-coat will limit the choice of potential low thermal conductivity oxides. Nevertheless, one approach may be to use an inner layer of YSZ, which is known to be phase compatible with alumina TGOs, and an outer layer of the new, lower conductivity oxide.
6. The maximum use temperature and times at temperatures for YSZ has yet to be determined with any accuracy as the kinetics of the transformation from the meta-stable form have not been established. Based on practical experience, however, it is felt that 500 hours at 1400°C is an upper limit for the purest of materials available.

7. New, lower thermal conductivity oxides that are stable to temperatures in excess of 1450^{o}C for thousands of hours are required for the next generation engines.
8. Identification of such oxides will need to rely on physical intuition and insight as computational methods are not sufficiently advanced to handle multi-component oxides. Nevertheless, the development of such computational methods together with improved potentials for heavier elements is considered a necessary long-term goal.
9. Non-destructive techniques based on photostimulated luminescence from the TGO beneath the thermal barrier coating continue to show promise as practical probes of the damage produced by cyclic oxidation.
10. The development of these techniques into practical tools needs further support as coating vendors and engine companies do not consider it their business to develop tools.
11. Initial reports of doping YSZ coatings, as well as other potential coatings, such as the zirconate pyrochlores, with rare-earth ions to create luminescence sensing capabilities show potential for non-contact, *in-situ* damage assessment, erosion thinning and, possibly, temperature measurement. The search is on to identify the particular rare-earth dopant that can be used for temperature monitoring whilst not degrading the life of the coating.
12. The use of luminescent dopants for sensing coating properties will need to move beyond the academic laboratories in order to be demonstrated as a viable methodology to industry and before they adopt it in practice.

Appendix A. Conference Announcement

Thermal and Environmental Barrier Coatings

To be held

August 17-22nd, 2003

At

Kloster Irsee,
Swabian Conference Center,
Germany

Organizing Committee

David Clarke (UC Santa Barbara), Carlos Levi (UCSB), Manfred Ruehle (Max Planck Institute, Stuttgart), Jerry Meier (U. Pittsburgh) and Tony Evans (UCSB).

Scientific Advisory Committee

Dr. Ram Darolia, GE Aircraft Engines, Cincinnati
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Professor Dr. M. Ruehle, Max Planck Insitut fur Metallforschung, Stuttgart
Professor Valter Sergo, University of Trieste, Italy
Professor Sanjay Sampath, Stony Brook, USA

Appendix B. Program

Session I. Introductory Session. Chair: M. Ruehle

08:45 – 09:00	Welcome
09:00 – 09:35	Michael Maloney, Pratt and Whitney ***Historical Development of Thermal Barrier Coatings***
09:35 – 10:10	Ram Darolia, GE Aerospace ***Industrial Perspective of TBCs for Aerospace***
10:10 – 10:40	Coffee Break
10:40 – 11:15	Stefan Lampenschafer, Siemens Power Systems ***Industrial Perspective of TBCs for Power Generation***
11:15 – 12:00	Anthony Evans, University of California, Santa Barbara ***TBCs as Interacting Multilayer Systems***
12:00 – 13:30	Lunch
13:30	**Session II: Oxidation Issues. Chair: A. G. Evans**
13:30 – 14:05	W. J. Quaddakers, Julich ***Oxidation of MCrAl Bond Coats***
14:05 – 14:40	Bruce Pint, Oak Ridge National Laboratory ***Oxidation of PtNiAl Aluminides***
14:40 – 15:10	Gerry Meier, University of Pittsburgh ***Growth Strain Accompanying Oxidation***
15:10 – 15:30	Afternoon Coffee Break
15:30 – 16:05	David Srolovitz, Princeton University ***Stress Development During Growth of Oxide Scales***
16:05 – 17:30	***Round-Table Discussion on Oxidation Stresses***
18:30 – 20:00	Dinner
20:00 – 21:00	**Discussion:** ***Future needs in understanding oxidation stresses***
21:00 – 22:00	Social Hour

Tuesday, 19th August

08:30	**Session III: Mechanical Properties of TBC systems.** **Chair: C. Levi**
08:30 – 09:05	Joachim Roesler, Technical University of Braunschweig ***Modeling TBC System Stresses and Failure***
09:05 – 09:40	Bill Clyne, University of Cambridge ***Microstructural and Property Changes in the Top Coat of Plasma-Sprayed Coatings During Service***
09:40 – 10:15	Kevin Hemker, John Hopkins University ***Bond Coat Mechanical Properties and Microstructural Evolution***
10:15 – 10:45	Coffee Break
10:45 – 11:20	Daniel Balint, Harvard University ***Modeling of Oxide Undulation Growth***
11:20 – 11:55	Alan Cocks, Leicester University ***Pegging Phenomena***
12:00 – 13:30	Lunch
13:30 – 16:30	***Round-Table Discussion on Mechanical Properties, Rumpling and Oxidation-Induced Instabilities***
18:30 – 20:00	Dinner
20:00	**Session IV. TBC Deposition Methods**
20:00 – 20:35	Nitin Padture, University of Connecticut ***Solution Precusor Plasma Spray for depositing TBCs***
20:35 – 21:10	David Wortman, General Electric Global Research Center ***Electron Beam Deposition of TBCs***
21:10 – 22:30	**Round Table Discussion and Social hour**

Wednesday, 20th August

Session V: Thermal Conductivity Measurements and Models

08:30 – 09:05	Daniele Fournier, CNRS ***Photothermal Experimental Techniques: Application to TBCs***
09:05 – 09:40	Ted Bennett, University of California, Santa Barbara ***In-situ Thermal Conductivity Measurements of Coatings***
09:40 – 10:15	Dongming Zhu, NASA Glenn Research Center ***Measuring Thermal Conductivity at High Temperatures***
10:15 – 10:45	Coffee Break
10:45 – 11:20	David Cahill, University of Illinois, Urbana ***Heat Transport by Lattice Vibrations: Disorder and Interfaces***
11:20 – 11:55	Simon Phillpott, Argonne National Laboratory ***Multiscale Simulation of Thermal Transport***
11:55 – 12:30	Ed Fuller, National Institute of Standards and Technology ***Predicting Physical Properties From Microstructure***
12:00 – 14:00	Lunch
14:00 – 14:30	***Poster Session: Recent Developments*** Brief Presentations by authors: Two Foil Maximum
14:30 – 18:00	***Poster Session with refreshments***
18:30 – 20:00	Dinner
20:00 – 22:00	**Round Table Discussions on Thermal Conductivity**

Thursday, 21st August

Session VII: Diffusion and Phase Stability. Chair: J. Meier

08:45 – 09:20	J.-C. Zhao, General Electric Global Research Center ***Efficient Exploration of Diffusion Multiples for Coating Design***
09:20 – 09:55	Tresa Pollock, University of Michigan ***Designing Bond-Coat / Superalloy Combinations***
09:55 – 10:30	Carlos Levi, University of California, Santa Barbara ***Phase Stability Studies***
10:30 – 11:00	Coffee Break
11:00 –12:00	**Roundtable Discussion on Inter-diffusion and Phase Stability Issues**
12:00 – 13:30	Lunch

Session VIII: Non-Destructive Evaluation and Future Coatings

13:30 – 14:05	Alan Atkinson, Imperial College, London ***Piezo-spectroscopy Studies of TGO Stress and Damage Evolution***
14:05 – 14:40	Ping Xiao, University of Manchester ***Impedance Spectroscopy of TBCs***
14:40 – 15:15	Maria Arana Antello, ALSTOM, Switzerland ***Geometrical and Loading Conditions Affecting TBC Failure***
15:15 – 15:30	Coffee Break
15:30 – 16:05	Joerg Feist, Southside Thermal Sciences ***Designing "Smart" TBCs: Rare-Earth Activated Materials***
16:05 – 16:40	Wolfgang Pompe, Technical University of Dresden ***TBCs for Novel Applications***
16:45 – 18:00	**Roundtable Discussions on NDE and Lifetime Predictions**
18:00 –19:00	**Organ Recital**
19:00 – 22:00	Conference Banquet and Social Hour

Friday, 22nd August

07:00 – 08:15	Breakfast
08:30 – 10:30	**Late Breaking Developments and Additional Discussions**
10:30 – 11:00	Coffee Break and Departures

APPENDIX C. POSTER CONTRIBUTIONS

Bernd Baufeld, German Aerospace Center (DLR), Germany
Influence of Bond-Coat Rumpling on Evolution of Delamination Cracks

T. Wakui, J. Malzbender, E. Wessel and R. W. Steinbrech,
Institute for Materials and Processes in Energy Systems, Julich
Microstructural Aspects of Segmentation and Delamination Fracture in Plasma Sprayed Thermal Barrier Coatings

Eric Jordan, University of Connecticut
Measurement of Oxide Stress and Associated Failure Modes

Valerie Reita, University Pierre et Marie Curie
Thermal Characterization of New Generation Coatings by "Mirage" Effect

Takashi Goto, Institute for Metals Research, Tohoku University
High-Speed Deposition of YSZ Coatings by Laser CVD

Shunkichi Ueno, National Institute of Advanced Industrial Science and Technology
High temperature Water Vapor Corrosion Resistance of Silicon Nitride with Lu-Si-O EBC

Franziska Traeger, Forschungszentrum, Julich
Fracture Mechanical Model for the Life-Time Evaluation of Plasma-Sprayed TBCs

Doni Jayaseelan, Synergy Materials Research Center, AIST
Development of New Candidate EBC Materials

Xijia Wu, Institute for Aerospace Research, National Research Council, Canada
Microstructural Damage Evolution in a Plasma Sprayed TBC

Gilles Cardosi, ONERA
Stress State in a EB-PVD Thermal Barrier Coating

Yasuo Matsunaga, Japan Fine Ceramics Center
Oxidation Behavior of Bond Coatings for EB-PVD TBCs

Mineaki Matsumoto, Japan Fine Ceramics Center
EB-PVD TBC with Low Thermal Conductivity and High-temperature Stability

John Nychka, University of California, Santa Barbara
Quantifying Cation Grain Boundary Diffusion in Thermally Grown Alumina

Shuqi Guo, Shijie Zhu and Yutaka Kagawa, Institute for Industrial Science, U. Tokyo
Effect of Loading Rate and Hold Time on Hardness and Young's Modulus of EB-PVD Thermal Barrier Coatings

Toru Tomimatsu, Shijie Zhu and Yutaka Kagawa, Institute for Industrial Science, University of Tokyo
Local Stress Distribution in Thermally Grown Oxide Layers of EB-PVD Thermal Barrier Coatings

Felicia Pitek, University of California, Santa Barbara
Phase Stability of Y^{3+} and Ta^{5+} Co-doped Zirconia for Thermal Barrier Coatings

V. Shemet, R. Anton, D. Sebold, W. J. Quadakkers and L. Singheiser, Forschungszentrum Julich
Oxidation Behavior of TBC Coated, Platinized MCrAlY Bond Coats During Thermal Cycling at 1000°C